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Parametric Studies on Particle Removal and Erosion in Nozzle Injection Megasonic Cleaning

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Abstract. The process of quickly removing abrasive particles of silica and ceria slurries is important in the use of CMP equipment. Megasonic cleaning of nozzle injection type is one of a variety of post-CMP cleaning methods and its performance including cleaning efficiency and erosion was explored experimentally with parametric studies. In the cleaning process, it is favorable to achieve both high efficiency and low damage. The cleaning efficiency was defined by particle removal efficiency (PRE) with a glass sample spin-coated with small silica particles; the damage was detected from mass loss of aluminum foils after the cleaning. The cleaning tests show that the performance of nozzle injection megasonic cleaning depends significantly on ultrasound frequency and water temperature. Toward more efficient and less erosive cleaning, the nozzle injection angle is also expected to play a key role.

Introduction

Post-CMP cleaning is the key process for advanced technology nodes in semiconductor manufacturing. It is necessary to quickly remove contaminant particles from substrates by polishing within the CMP equipment. To achieve better cleaning performance, different types of physical cleaning methods (of contact and non-contact types) are applied in the post-CMP cleaning. One promising candidate of non-contact cleaning methods is based on megasonic water flow of nozzle injection type [1]; recent studies suggest that cavitation bubbles in water flow under megasonic wave irradiation play a key role in particle removal [2, 3, 4]. However, megasonic cleaning with acoustic cavitation is known to have a side effect, giving rise to surface damage due to violent bubble collapse. In the context of post-CMP cleaning, it is favorable to avoid wafer defects as a result of cavitation erosion, while the cleaning efficiency is maintained. In this study, the performance of nozzle injection megasonic cleaning was evaluated in terms of particle removal efficiency and cavitation erosion; the cleaning tests were performed with varying the ultrasound frequency, injection angle, and water temperature.

Experimental Method

Particle Removal. The schematic of nozzle injection megasonic cleaning is shown in Figure 1. The experimental apparatus consists of a megasonic water flow cleaner (QUAVA Spot, KAIJO), a water container, a pump, a volume flow meter, and a glass plate with a diameter of 100 mm. The water was pumped to the megasonic water flow cleaner nozzle head that is equipped with a piezoelectric transducer for ultrasound irradiation. The water under the ultrasound irradiation was injected through a circular nozzle onto glass plate whose surface is spin-coated with silica particles of diameter at 0.25 μm (MS-B200, Mikasa). The injection distance (from the nozzle exit to the jet collision at the glass surface) was set at 20 mm. For the cleaning tests with varying the water temperature, care was taken for the heated water to be under dissolved-gas saturation. The haze method [5] was applied to define the cleaning efficiency, which is based on light scattering from the glass surface (before and after megasonic cleaning) capture by a digital camera at 45 degrees from back illumination by a halogen lamp in a dark room, as shown in the schematic in Figure 2. Particle Removal Efficiency (PRE) is used to evaluate the cleaning efficiency and defined based on the intensity of light scattering from particles on the cleaning sample before and after the 60-s cleaning [4]; PRE = 0% means that no particles are removed, while PRE = 100% means that all particles are removed. To examine the non-uniformity in the cleaning efficiency, PRE was defined at three different domains A to C as depicted in Figure. 2 (b); the domain A is set at the center of the glass plate, while the domain C is close to the edge of the glass plate. As listed in Table 1(a), PRE was evaluated with varying the ultrasound frequency, nozzle injection angle, and water temperature.

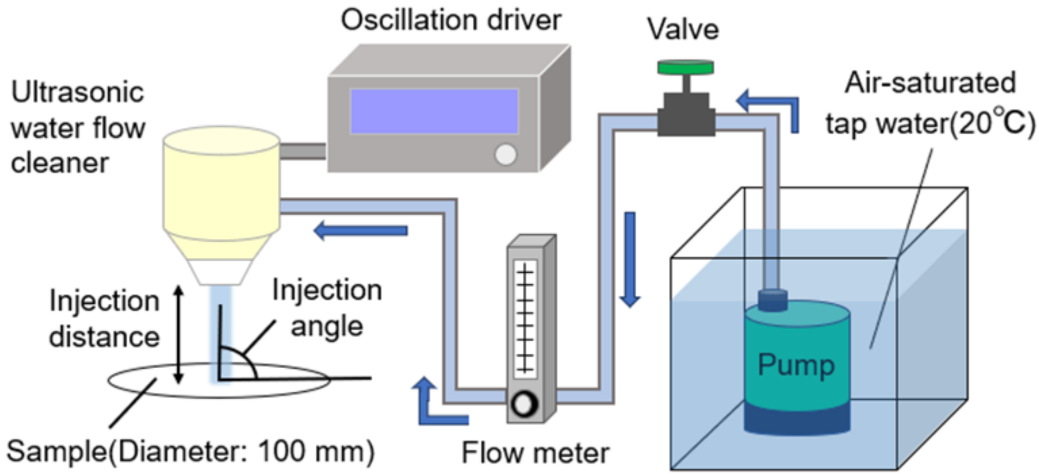

Figure 1: Schematic of the experimental setup with an ultrasonic water flow cleaner, a water container, a pump, a volume flow meter, and a glass plate with a diameter of 100mm. The cleaning sample is a glass plate (100 mm in diameter) spin-coated with silica particles (0.25 µm in diameter). The ultrasound frequency, injection angle, and water temperature were treated as parameters.

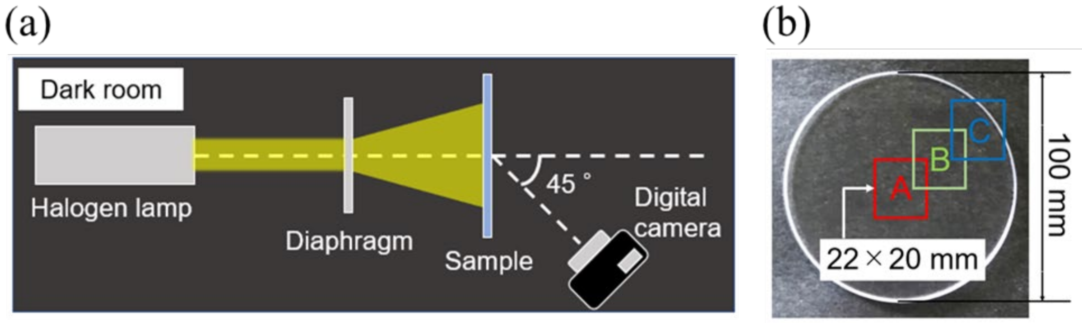

Figure 2: Evaluation of the cleaning efficiency based on the haze method. (a) Optical system for the measurement of intensity of light scattering from particles. (b) PRE evaluation domains A to C.

Erosion. It is generally known that megasonic cleaning tends to cause erosion damage, and there is a suspicion of defects [6]. To evaluate erosive effects of the nozzle injection megasonic cleaning, we applied the same experimental approach as in Figure 1 and now used a glass plate covered with an aluminum foil (12 µm in thickness). After the 60-s ultrasound irradiation, the mass loss of the aluminum foil was measured by an electronic analytical scale, with varying the parameters as in Table 1(b).

Table 1: The parameters used in the nozzle injection megasonic cleaning tests for evaluation of (a) particle removal efficiency (PRE) and (b) erosion with aluminum foils.

(a)

Parameter Description	Terms
Frequency (MHz)	0.43, 0.95, 3.0
Nozzle inclination (degree)	90 (vertical), 60 (Inclined)
Temperature (°C)	15, 20, 25, 30, 35

(b)

Parameter Description	Terms
Frequency (MHz)	0.43, 3.0
Nozzle inclination (degree)	90 (vertical)
Temperature (°C)	15, 25, 35

Results and Discussion

Particle Removal. The nozzle injection megasonic cleaning was evaluated for various parameters; see the visualization in Figure 3 and the PRE results in Figure 4. The zero PRE for the case without ultrasound irradiation indicates that hydrodynamic effects of the water jet itself are not sufficient for particle removal. In domain A and B, the thickness of the liquid film flow is so thin that the acoustic pressure is expected to be large enough to make cavitation bubbles active; large-amplitude oscillation of near-wall bubbles will produce large wall shear stress [7], contributing to particle removal. On the other hand, in domain C, the film thickness is increased as a result of the hydraulic jump, giving rise to a reduction in the acoustic pressure with less active cavitation bubbles. Interestingly, the PRE value (defined along the negative part of the x axis in Figure 3(b)) is increased by having the inclined injection (60°) for the case of 3.0 MHz ultrasound irradiation; see Figure 4(b). This is consistent with the observation that the thin liquid film region is further extending in the case of the highest-frequency ultrasound as in Figure 3(c). It follows from the cases with ultrasound irradiation and right injection angle (90°) in Figure 4(a) that the PRE values in domain A and B are relatively high but relatively low in domain C for all the ultrasound frequency.

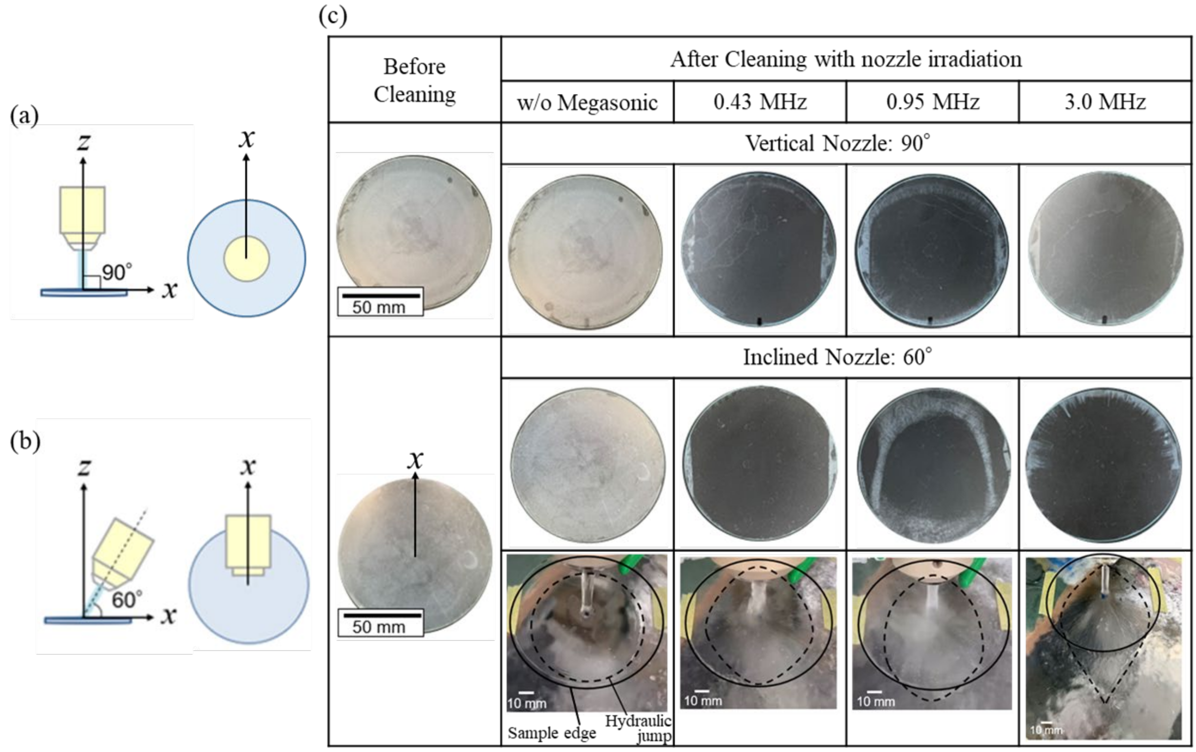

Figure 3: Visualization of the nozzle injection megasonic cleaning at 50 W with different ultrasound frequency and injection angle. (a,b) Coordinate definition, respectively, for vertical injection (90°) and inclined injection (60°). (c) Images of light scattering at the sample surface with backlighting, together with visualization of spreading liquid flow over the sample for the inclined injection.

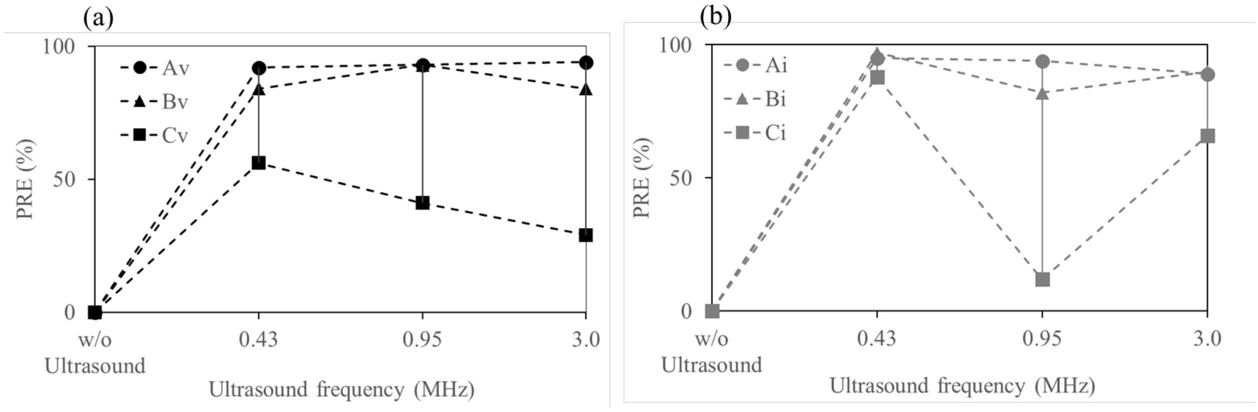

Figure 4: PRE results in domain A to C (as defined in Fig. 2(b)), without ultrasound and with ultrasound (0.43 MHz, 0.95 MHz, 3.0 MHz). (a) Vertical injection case (90°). (b) Inclined injection case (60°). The domain A to C is defined along the negative part of the x axis in Figure 3(b).

Next, thermal effects of the (gas-saturated) water on the PRE results are examined from the leaning tests with varying the water temperature (but with the ultrasound frequency fixed at 0.95 MHz); see Figure 5. The zero PRE is again obtained for the case without the ultrasound irradiation. For the case with the irradiation, the PRE is found to increase by having higher temperature (up to 35°C). As the temperature is increased, the surface tension of water is reduced so that more cavitation bubbles can be nucleated, leading to larger PRE values. We speculate that a further increase in the temperature will give rise to less active motion of cavitation bubbles due to thermal effects [8]; there will exist an optimal temperature at which the cleaning efficiency becomes aximal. To explore the optimal water temperature, there is a need to perform additional tests with a broader range of the temperature.

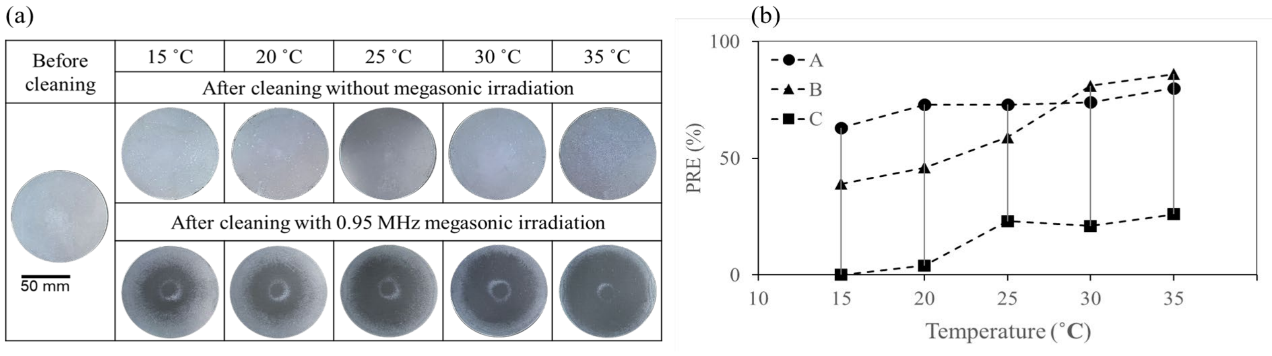

Figure. 5: Effects of the water temperature (15°C to 35°C) on the PRE for the case of 0.95 MHz ultrasound at 20 W and vertical injection angle (90°). (a) Images of light scattering at the sample surface before and after the 60-s cleaning. (b) PRE results in domain A to C (as defined in Fig. 2(b)) with the different temperature.

Erosion. When it comes to evaluating the cleaning performance of the nozzle injection megasonic cleaning, there is also a need to examine its erosive effects in addition to PRE. Under underwater ultrasound irradiation, surface damage will be created by violent collapse of cavitation bubbles. Figure 6(a) presents a SEM image of erosion on an insulating low-k film wafer (k = 2.4) after the nozzle injection megasonic cleaning; the size of the erosion is on the order of microns and thus comparable to acoustic cavitation bubbles under the megasonic irradiation [9,10], indicating that cavitation erosion can appear in this cleaning process. To explore what factors can minimize the erosion effects, we performed erosion tests with the same setup in Figure 1 but with the glass plate covered with an aluminum foil (12 μm in thickness). From visualization of the foil surface (in Figure 6(b)) and the weight reduction rate (in Figure 6(c)), it is confirmed that the higher frequency and higher temperature can contribute to a reduction in the erosive effects. It is instructive to note that bubble dynamics in hotter water become less violent due to thermal effects [8]; the cleaning with higher-temperature will be less erosive. However, there is a need to be careful that the higher water temperature will also accompany lower cleaning efficiency. Such a trade-off relation between more efficient and less erosive cleaning needs to be considered for better cleaning performance.

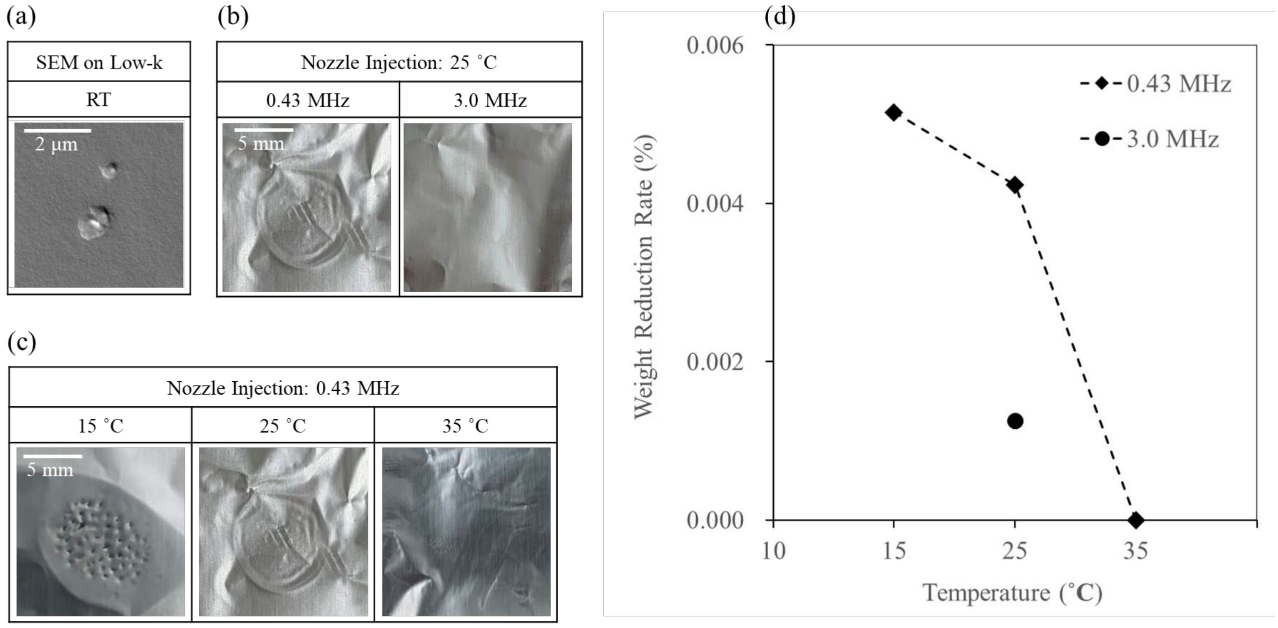

Figure 6: Evaluation of the erosive effects of the nozzle injection megasonic cleaning at 50 W. (a) SEM image of the erosion on low-K. (b) Visualization of the foil after the 60-s ultrasound irradiation at different frequency with aluminum foils (12 µm in thickness). (c) Visualization of the foil after the 60-s 0.43 MHz ultrasound irradiation at different temperature with aluminum foils (12 µm in thickness). (d) Mass reduction rate (%) with varying ultrasound frequency and water temperature.

Conclusion

The PRE and erosion tests with a nozzle injection megasonic cleaning were performed with varying parameters including ultrasound frequency (0.43 MHz to 3 MHz), injection angle (90° or 60°) and water temperature (15°C to 35°C), exploring the optimal operation conditions for more efficient and less erosive cleaning. The inclined water jet injection with higher ultrasound frequency will be beneficial to increase PRE with thinner liquid film flow over cleaning targets. In this water temperature range, the PRE value is found to increase as the temperature increases with which more cavitation bubbles are nucleated. It is also confirmed that the higher ultrasound frequency and higher temperature can contribute in a reduction of cavitation erosion.

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